

Properties of hadrons in a chiral model with (axial-)vector mesons

Francesco Giacosa

Institut für Theoretische Physik

Johann Wolfgang Goethe - Universität, Max von Laue-Str. 1

D-60438 Frankfurt, Germany

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Abstract

Recent advances in the development of a chiral linear σ -model with (axial-)vector mesons are presented. The model is based on the basic requirements of global chiral symmetry and dilatation invariance. The role of (axial-)vector states turns out to be crucial both in the meson and the baryon sectors. First results at nonzero temperature and density are discussed.

1 Introduction

The description of the masses and the interaction of low-lying hadron resonances is a central subject of high-energy physics [1]. To this end, a lot of effort has been put in the development of quantum field theoretical effective hadronic Lagrangians: chiral perturbation theory [2], its extension with vector mesons [3], and linear σ -model(s) [4, 5, 6, 7, 8] represent the most outstanding examples.

In this work we concentrate on the theoretical advances of the latter class of hadronic theories: namely, we focus on a linear σ -model with (axial-)vector mesons, which aims to describe (almost all) hadrons up to 1.7 GeV, both in the vacuum and at nonzero temperature and density. Although the linear σ -model with scalar and pseudoscalar mesons has been extensively studied, its generalization with (axial-)vector mesons was up to now not systematically investigated. Preliminary studies in this direction have been performed for the case $N_f = 2$ only in Ref. [5, 6], where N_f is the number of quark flavors. Moreover, in Ref. [5] a different theoretical principle based on the so-called local realization of chirally symmetry was employed, and in Ref. [6] only ‘half’ of the fields was taken into account (the scalar isotriplet a_0 meson and the pseudoscalar meson η were neglected).

The construction of the Lagrangian of the here considered linear σ model follows two basic requirements stemming from the underlying QCD theory [7, 8, 9]: (i) Global chiral symmetry $U(N_f)_L \times U(N_f)_R$. (ii) Dilatation invariance, with the exception of terms stemming from the gauge sector (scale-anomaly and $U(1)_A$ anomaly, in accord with QCD) and of terms which describe the non-zero values of the quark masses (explicit breaking of the dilatation symmetry). All other terms are thus described by dimensionless coupling constants.

The assignment of the fields of the model with the resonances listed in the PDG [10] is straightforward for the multiplets $J^{PC} = 0^{-+}$, $J^{PC} = 1^{--}$, and $J^{PC} = 1^{++}$. As usual, the scalar meson multiplet $J^{PC} = 0^{++}$ is problematic: the present σ -model shows indeed results which are at odd with previous σ -model studies. Namely, the preferred scenario is realized for scalar mesons between 1-2 GeV. This result is a consequence of the inclusion of (axial-)vector degrees of freedom, which generate peculiar

interference effects in the decay amplitudes. More in general, the role of the (axial-)vector states is relevant in both the meson and baryon sectors for a proper description of the phenomenology.

Some of the resonances of the multiplet $J^{PC} = 1^{++}$ were interpreted in Ref. [11] as dynamically generated states. However, as discussed in Ref. [9], unitarization procedures can regenerate preformed quark-antiquark states which were formally integrated out in order to obtain the low-energy effective Lagrangians of Refs. [2] and [3]. Thus, the interpretation of the states $J^{PC} = 1^{++}$ as a quark-antiquark multiplet is, in agreement with Ref. [10], upheld¹.

The present proceeding paper is organized as follows: in Sec. 2 and 3 we review the mesonic and baryonic sectors respectively, and in Sec. 4 we present our conclusions and outlooks.

2 Meson sector

The basic ingredients of the linear σ -model in the meson sector are the glueball/dilaton field G , the (pseudo)scalar multiplet $\Phi = (S^a + iP^a)t^a$ and the left-handed and right-handed vectorial multiplets $L^\mu = (V^{a,\mu} + A^{a,\mu})t^a$, $R^\mu = (V^{a,\mu} - A^{a,\mu})t^a$ (the matrices t^a are the generators of the group $U(N_f)$). The mesonic Lagrangian \mathcal{L}_{mes} which fulfills the criteria of (i) global chiral symmetry and (ii) dilatation invariance takes the following form for a generic number of flavors N_f [7, 8]:

$$\begin{aligned} \mathcal{L}_{mes} = & \frac{1}{2}(\partial_\mu G)^2 - V_{dil}(G) + \text{Tr} \left[(D^\mu \Phi)^\dagger (D_\mu \Phi) - aG^2 \Phi^\dagger \Phi - \lambda_2 (\Phi^\dagger \Phi)^2 \right] - \lambda_1 (\text{Tr}[\Phi^\dagger \Phi])^2 + \\ & + c(\det \Phi^\dagger - \det \Phi)^2 + \text{Tr}[\hat{\varepsilon}(\Phi^\dagger + \Phi)] - \frac{1}{4}\text{Tr}[(L^{\mu\nu})^2 + (R^{\mu\nu})^2] \\ & + \frac{b}{2}G^2\text{Tr}[(L^\mu)^2 + (R^\mu)^2] + \frac{1}{2}\text{Tr}[\hat{\delta}(L^\mu)^2 + (R^\mu)^2] - 2ig_2 (\text{Tr}[L_{\mu\nu}[L^\mu, L^\nu]] + \text{Tr}[R_{\mu\nu}[R^\mu, R^\nu]]) \\ & + h_2\text{Tr}[\Phi^\dagger L_\mu L^\mu \Phi + \Phi R_\mu R^\mu \Phi] + 2h_3\text{Tr}[\Phi R_\mu \Phi^\dagger L^\mu] + \dots, \end{aligned} \quad (1)$$

where $D^\mu \Phi = \partial^\mu \Phi - ig_1(L^\mu \Phi - \Phi R^\mu)$ and dots represent further terms which are either large- N_c suppressed or unimportant in the evaluation of decays and (on-shell) scattering lengths. Following comments are in order:

(i) Besides the dilaton field G , the mesonic fields of the model are quark-antiquark fields. This can be easily seen by studying the so-called large- N_c limit [13]: the masses are N_c -independent and the widths scale as N_c^{-1} [7].

(ii) The dilaton potential reads $V_{dil}(G) = \frac{1}{4} \frac{m_G^2}{\Lambda_G^2} \left[G^4 \ln \left(\frac{G}{\Lambda_G} \right) - \frac{G^4}{4} \right]$ [14]. The parameter $\Lambda_G \sim N_c \Lambda_{QCD}$ has dimension energy and sets the energy scale of the theory.

(iii) The $U(1)_A$ anomaly term is parametrized by the parameter c , which has dimension $[\text{Energy}]^{4-2N_f}$.

(iv) In the (pseudo)scalar sector the explicit symmetry breaking of both chiral and dilatation symmetries is encoded in the matrix $\hat{\varepsilon} \propto \text{diag}\{m_u, m_d, m_s, \dots\}$, where the entries are the bare quark masses. Similarly, in the (axial-)vector sector the analogous diagonal matrix $\hat{\delta}$ has been introduced.

(v) Chiral symmetry breaking takes place when the parameter a is negative. In fact, upon the condensation of the field $G = G_0$, the ‘wrong’ mesonic mass sign is realized for $aG_0^2 < 0$.

(vi) The calculations are performed at tree-level. The inclusion of loops is a task for the future, but only slight changes are expected [15]. Here we mostly concentrate on decay widths; it is in this respect interesting to notice that the latter do not correspond to an exponential law as function of time because large variations take place for hadrons [16].

Once the shifts of the scalar fields $G \rightarrow G_0 + G$ and $\Phi \rightarrow \text{diag}\{\sqrt{2}\sigma_N, \sqrt{2}\sigma_N, \dots\} + \Phi$, where the first term is a diagonal matrix with the quark-antiquark condensates, and necessary redefinitions of the

¹The example of tensor mesons is clarifying: these states can be also obtained via ‘dynamical generation’, but fulfill to a very good accuracy all the required properties to be interpreted as a quark-antiquark meson nonet [12].

pseudoscalar and axial-vector fields have been performed, the explicit calculations of physical processes are lengthy but straightforward.

The case $N_f = 2$ with frozen glueball ($m_G \rightarrow \infty$) has been studied in Ref. [7]. It has been shown that the inclusion of (axial-)vector mesons has a strong influence on the overall phenomenology. For instance, the width of the scalar meson σ (the chiral partner of the pion) decreases substantially w.r.t. the case without (axial-)vector mesons: for this reason, the identification of this field with the resonance $f_0(600)$ is not favoured, because the theoretically evaluated width is smaller than 200 MeV, while the experimental one is larger than 400 MeV. On the contrary, the identification of the σ field with the resonance $f_0(1370)$ turns out to be in agreement with the experimental results. The description of the (axial-)vector resonances is also in agreement with the experiments reported in Ref. [10].

In Ref. [8] the glueball with a bare mass of about $m_G \sim 1.5$ GeV, in agreement with the lattice calculation of Ref. [17], has been studied for the first time in a chiral model with (axial-)vector mesons. (For a compilation of other approaches see Refs. [18] and refs. therein). The state $f_0(1500)$ results as the predominantly (75%) glueball state, and the rest of the phenomenology is only slightly affected w.r.t. the previous case, in which $m_G \rightarrow \infty$. Moreover, also the gluon condensate can be evaluated and turns out to be in agreement with lattice results.

Future works in the meson sector consist in the study of the cases $N_f = 3$ and $N_f = 4$, respectively. Preliminary results of the former case were already presented in conference proceedings [19] and a systematic study will be concluded soon. Interestingly, when increasing N_f of one unit, only two additional parameters, both related to the included bare quark mass, are necessary. Thus, enlarging the model is straightforward (although it implies lengthy calculations) and allows for more stringent checks of the model.

Finally, being the scalar states above 1 GeV, a natural question is the assignment of the existing resonances below 1 GeV. According to the Jaffe's interpretation [20] these resonances can be interpreted as a scalar nonet of tetraquark states, see Refs. [21] and refs. therein. The coupling of tetraquark fields to the chiral model is possible by following the prescription of Ref. [22]. The study of this scenario and the arising mixing patterns represents an outlook. Interestingly, in the simplified case $N_f = 2$ there is only one scalar tetraquark field χ , which can be identified with the resonance $f_0(600)$; its coupling to the chiral model has been discussed also at nonzero T in Ref. [23], where it has been shown that it can substantially influence the properties of the chiral phase transition. This study shows that the correct interpretation of scalar resonances is mandatory not only for a correct understanding of spectroscopy in vacuum, but also toward a proper description of hadrons at nonzero temperature.

3 Baryon sector

The inclusion of the nucleons and their chiral partner into the model was performed in Ref. [24]. The aim is the description of vacuum phenomenology (such as pion-nucleon scattering lengths and decays), the origin of the nucleon mass, the properties of nuclear matter, and the chiral phase transition at nonzero density.

In the so-called mirror assignments [25] one starts with two baryonic fields Ψ_1 and Ψ_2 transforming under chiral transformation as

$$\Psi_{1R} \longrightarrow U_R \Psi_{1R}, \quad \Psi_{1L} \longrightarrow U_L \Psi_{1L}, \quad \Psi_{2R} \longrightarrow U_L \Psi_{2R}, \quad \Psi_{2L} \longrightarrow U_R \Psi_{2L} \quad . \quad (2)$$

While Ψ_1 transforms as usual, Ψ_2 transforms in a ‘mirror way’. Due to this characteristic it is possible to write down the following Lagrangian in the baryonic sector for $N_f = 2$:

$$\begin{aligned} \mathcal{L}_{bar} = & \bar{\Psi}_{1L} i \gamma_\mu D_{1L}^\mu \Psi_{1L} + \bar{\Psi}_{1R} i \gamma_\mu D_{1R}^\mu \Psi_{1R} + \bar{\Psi}_{2L} i \gamma_\mu D_{2R}^\mu \Psi_{2L} + \bar{\Psi}_{2R} i \gamma_\mu D_{2L}^\mu \Psi_{2R} \\ & - \hat{g}_1 (\bar{\Psi}_{1L} \Phi \Psi_{1R} + \bar{\Psi}_{1R} \Phi^\dagger \Psi_{1L}) - \hat{g}_2 (\bar{\Psi}_{2L} \Phi^\dagger \Psi_{2R} + \bar{\Psi}_{2R} \Phi \Psi_{2L}) + \mathcal{L}_{mass} \quad , \end{aligned} \quad (3)$$

whereas $D_{iR(L)}^\mu = \partial^\mu - ic_i R(L)^\mu$ with $i = 1, 2$ and the chirally invariant mass term $\mathcal{L}_{\text{mass}}$ reads

$$\mathcal{L}_{\text{mass}} = -(\alpha\chi + \beta G)(\bar{\Psi}_{1L}\Psi_{2R} - \bar{\Psi}_{1R}\Psi_{2L} - \bar{\Psi}_{2L}\Psi_{1R} + \bar{\Psi}_{2R}\Psi_{1L}). \quad (4)$$

The chirally invariant fields χ and G represent the scalar tetraquark and glueball, respectively. (Note, the term $\mathcal{L}_{\text{mass}}$ would not be possible if the field Ψ_2 would transform as Ψ_1 .) All the introduced coupling constants are dimensionless, as required by the requirement of dilatation invariance.

Upon generation of the tetraquark and gluon condensates χ_0 and G_0 , a nonvanishing chiral mass emerges

$$m_0 = \alpha\chi_0 + \beta G_0, \quad (5)$$

which represents the mass contribution to the nucleon which does *not* stem from the chiral (quark-antiquark) condensate $\sigma_N = \phi$. The nucleon and its partner arise upon diagonalization of Ψ_1 and Ψ_2 :

$$\begin{pmatrix} N \\ N^* \end{pmatrix} = \frac{1}{\sqrt{2 \cosh \delta}} \begin{pmatrix} e^{\delta/2} & \gamma_5 e^{-\delta/2} \\ \gamma_5 e^{-\delta/2} & -e^{\delta/2} \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}, \quad \cosh \delta = \frac{m_N + m_{N^*}}{2m_0}, \quad (6)$$

whereas the masses of N and N^* are a combination of m_0 and the chiral condensate ϕ :

$$m_{N,N^*} = \sqrt{m_0^2 + \left(\frac{\hat{g}_1 + \hat{g}_2}{4}\right)^2 \phi^2} \pm \frac{(\hat{g}_1 - \hat{g}_2)\phi}{4}. \quad (7)$$

The study of the vacuum's properties of this model has been presented in Ref. [24]. Upon a fitting to known experimental and lattice values, the value of m_0 turns out to be non-negligible: $m_0 = 460 \pm 136$ MeV. As a further step the pion-nucleon scattering lengths can be calculated and are in agreement with the experimental data. (In particular, one has $a_0^{(-)} = (6.04 \pm 0.63) 10^{-4}$ MeV $^{-1}$, which should be compared with $a_0^{(-)\text{exp}} = (6.4 \pm 0.1) 10^{-4}$ MeV $^{-1}$. The isospin-even scattering length $a_0^{(+)}$ depends on the scalar meson sector and is therefore more subtle, see details in Ref. [24].) It is in this respect important to stress that (i) (axial-)vector mesons play a non-negligible role for the pion-nucleon scattering lengths and (ii) the use of the naive assignment, which is equivalent to the case without the chiral partner of the nucleon, delivers unacceptable result for the scattering lengths.

The extension to nonzero density has been investigated in Ref. [26], in which the parameter β in Eq. (4) has been set to zero. It is thus assumed that the tetraquark state dominates: an important outcome of Eq. (4) is the generation of a tetraquark-exchange term for the nucleon-nucleon interaction, which intuitively corresponds to the exchange of diquarks between nucleons. The corresponding resonance is the lightest scalar state $f_0(600)$. As shown in Ref. [26] it is possible to describe nuclear matter saturation for the very same value of m_0 obtained in the vacuum. Moreover, the nuclear matter compressibility turns out to be in agreement with the experimental value. For increasing density a first order chiral phase transition takes place at $\rho \simeq 2\rho_0$, at which both quark-antiquark and tetraquark condensates drop to (almost) zero. Interestingly, in the proposed approach the binding of nuclear energy is possible in virtue of the existence of a light tetraquark field. An amusing consequence is that nuclear matter seems to be a peculiarity of our $N_c = 3$ world, which does not hold when increasing N_c [27].

4 Conclusions and outlooks

In this work recent results obtained with a linear σ -model with (axial-)vector mesons have been presented. The inclusion of (axial-)vector degrees of freedom is a necessary step toward a proper description of both vacuum and medium properties of hadrons.

Various outlooks of the described approach are planned: (i) The extension to $N_f = 3$ is an ongoing project with preliminary results presented in Ref. [19]. Only two additional parameters w.r.t. the

$N_f = 2$ case are needed. (ii) Inclusion of a light tetraquark nonet and evaluation of mixing with the quark-antiquark states. (iii) The extension to $N_f = 3$ allows to include charmed mesons into the chiral model (for the first time with (axial-)vector states). Also in this case only two additional parameters w.r.t. the case $N_f = 3$ are necessary. (iv) The pseudoscalar glueball with a lattice predicted mass [17] of about 2.6 GeV can be easily incorporated into the model. Both outlooks (iii) and (iv) are interesting in view of the planned Panda experiment [28] at the FAIR facility at GSI/Darmstadt. (v) Evaluation of weak decays of the τ -lepton into hadrons. (vi) Calculation of nucleon-nucleon scattering and related dilepton production, e.g. Ref. [29]. (vii) Extension of the study at nonzero T . Preliminary works were performed with simplified versions of the models in Refs. [23, 30], but a systematic study needs to be performed. Care is needed in view of the discussion presented in Ref. [31], where it is shown that a modification of purely hadronic models is necessary in order to be in agreement with basic properties of the large- N_c limit. (viii) Further studies of properties at nonzero density, with special attention to the quarkyonic phase and to non-homogeneous condensates [32], are planned. The outlooks (vii) and (viii) can be combined in order to achieve a complete picture of the chiral phase diagram of QCD.

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